Appendix V: Sodium-Cooled Fast Reactor

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SODIUM-COOLED FAST REACTOR (SFR)

The sodium-cooled liquid metal reactor (SFR) system features a fast-spectrum reactor and closed fuel recycle system. The primary mission for the SFR is the management of high-level wastes, and in particular, management of plutonium and other actinides. With innovations to reduce capital cost the mission can extend to electricity production, given the proven capability of sodium reactors to utilize almost all of the energy in the natural uranium.

A range of plant size options is available for the SFR, ranging from modular systems of a few hundred MWe to large monolithic reactors of 1500–1700 MWe. Sodium core-outlet temperatures are typically 550ºC. The primary coolant system can either be arranged in a pool layout (a common approach, where all primary system components are housed in a single vessel), or in a compact loop layout, favored in Japan. For both options, there is a relatively large thermal inertia of the primary coolant. A large margin to coolant boiling is achieved by design, and is an important safety feature of these systems. Another major safety feature is that the primary system operates at essentially atmospheric pressure. A secondary sodium system acts as a buffer between the radioactive sodium in the primary system and the energy conversion system in the power plant.

Two fuel options exist for the SFR: (1) mixed uranium-plutonium oxide (MOX), or (2) mixed uranium-plutonium-zirconium metal alloy (metal). The experience with MOX fuel is considerably more extensive than with metal.

The SFR activities will be under the overall leadership of Argonne National Laboratory. The development schedule for the SFR is shown in Figure 1.

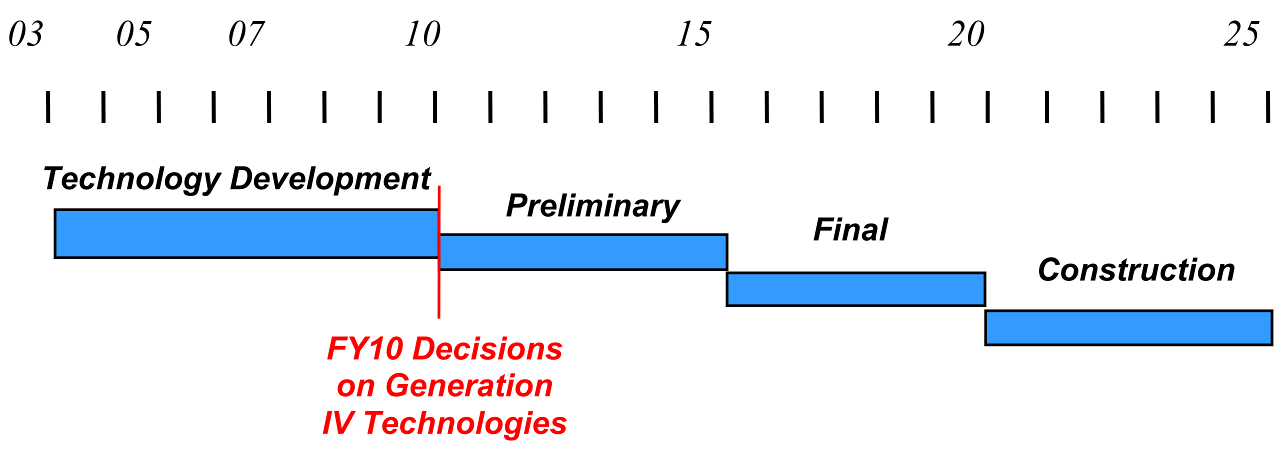

Figure 1. SFR Development schedule

1 SYSTEM DESIGN AND EVALUATION

Sodium-cooled systems have been significantly developed and may not require as much system design R&D as other Generation IV systems. R&D is nevertheless needed for demonstration of the design and safety characteristics, especially with fuels containing minor actinides, and to optimize the design with innovative approaches to meet the objectives of the specific missions of Generation IV, primarily actinide management.

1.1 System Design

Innovations for the SFR systems include means to reduce capital cost. Both economy of scale and economy of modular factory fabrication and just-in-time capacity additions are proposed – i.e., strategies optimized for the financial parameters that may exist in regulated or deregulated markets. For monolithic, loop-type reactor designs, innovations include simplification based on reducing the number of loops and simplifying and increasing the size of components. Here the availability of qualified advanced materials (for example 12Cr-1Mo) is considered a technology gap requiring viability R&D.

Additional R&D needs have been identified for basic nuclear data enhancements for certain minor actinides, since they are recycled in the SFR. Recommended R&D also includes operations and maintenance items, such as the development of under-sodium viewing and/or ultrasonic testing in sodium, development of high-reliability steam generators, and development or selection of materials for components and structures.

SFR reactors will also benefit from innovative balance of plant simplifications and this is discussed under section 4, Energy Conversion.

The basis for the actinide management strategy needs to be well established. Studies in the fuel cycle options for actinide management are programmatically under the ACFI program.

1.2 Safety

In reactor safety the technology gaps center around three general areas: basic properties; assurance of passive safety response, including the modeling and validation of the models through experimentation; and the technology for evaluation of bounding events. Basic property needs include data on fuel performance for SFR fuels that contain minor actinides (MA) (see 3, Fuel and Fuel Cycle). For modeling and validation of passive safety, it will be necessary to verify the reactivity feedback mechanisms of the MA-bearing fuels and to establish their transient fuel behavior prior to failure. These safety R&D needs related to basic properties and passive safety confirmation have been estimated to relate to performance R&D. Viability R&D focuses on the technology for evaluating bounding accidents.

2 MATERIALS

Materials-related issues are covered under different subsections. These issues include: (1) fuel-cladding constituent interdiffusion behavior for MA-bearing fuels, (2) development of high-strength steels for use in structures and piping to improve economics, and (3) improved materials for recycle systems.

3 FUELS AND FUEL CYCLE

SFR fuels will contain a relatively small fraction of minor actinides and a small amount of fission products. The systems based on MOX fuel are primarily under development in Japan and their preferred recycle option is an advanced aqueous process. Metal-fueled reactor systems, under development in the U.S., use a pyroprocessing recycle process as the preferred fuel cycle option.

The GIF countries leading the development of the SFR will develop the draft strategy for proliferation resistance and physical protection. Studies undertaken under the ACFI program related specifically to pyroprocessing of metal fuels can complement the draft strategy.

3.1 Advanced Aqueous Process

Viability R&D work remains to demonstrate the high actinide recoveries (99.9%) and the proliferation resistance features of the process.

Demonstration of remote fabrication processes for ceramic fuels, whether the process is simplified pellet fabrication or one of the particle compaction approaches, is also needed.

3.2 Pyroprocess

It will be essential to conduct plutonium and minor actinide extraction experiments from electrorefiners at a much larger scale than has been done until now (~50 g plutonium). Significant work on electrorefiner salt cleanup and high-level waste form production needs to be done in order to achieve the very high actinide recoveries (~99.9%) that are the objective of the process. It is important to develop any secondary waste stream treatment that may become necessary to achieve this recovery goal. Also, it is necessary to complete certification of the two high-level waste forms (metal and ceramic) for repository disposal.

The viability issues can be summarized as follows:

1. Scale process from laboratory to engineering scale
2. Demonstration of recovery process for transuranics
3. Development of salt cleanup to extract actinides for waste processing
4. Development of ion exchange systems for ceramic waste volume reduction

Viability items for pyroprocess are functionally part of the ACFI program and are not included in the SFR development plan under Generation IV.

3.3 Fuels

A significant technology gap for fast reactor systems using recycled fuel is a need for performance data and transient safety testing of fuel that has been recycled using prototypic processes.

The viability issues identified with SFR fuels are summarized as follows:

Oxide fuels

- Fabricability, as included under fuel cycle

Metal fuels

- Confirmation of properties of minor-actinide (MA) bearing fuels
- Confirmation of fuel-cladding constituent interdiffusion behavior for MA-bearing fuels
- Modeling of fuel-cladding interdiffusion and fuel constituent migration

The viability items for SFR fuel development is also programmatically under the ACFI program and are not included in the SFR development plan here.

4 ENERGY CONVERSION

The basic R&D in energy conversion for SFR systems is (1) to establish the technical basis for coupling supercritical carbon dioxide Brayton cycles to sodium-cooled fast reactors, and (2) to develop revolutionary steam generator technologies to minimize plant cost. The first activity, coupling to a supercritical carbon dioxide cycle, is expected to take place as part of an effort on Crosscutting Energy Products R&D.

5 FY 2004 WORK SCOPE

The SFR activities in FY2004 are only in the area of interaction with the GIF Steering Committee, as described below. Associated funding is shown in Table 1.

5.1 Interaction with GIF on SFR

Interface with Generation IV International Forum, in particular with the GIF countries leading the SFR development effort to optimize effectiveness of R&D plan and to maintain cognizance of progress in SFR development. Interface with the ACFI Program on fuel and fuel cycle development activities for their relevance to the SFR. Interface with the crosscutting activities for relevance to SFR.

Table 1. Summary of SFR Level 4 Tasks for FY 2004 ($K)

Task	Total
Interaction with GIF	$
Total	**$**

No milestones are associated with the activities at the target level in FY 2004.

6 FY 2005 WORK SCOPE

The Fiscal year 2005 scope is divided into two areas: system design & evaluation and coordination with GIF. Associated funding is shown in Table 2.

The following subsections describe first the required scope followed by a description of the scope that can be accomplished with the expected available funding.

6.1 System Design and Evaluation

In order to support the technology selection in FY2010, the viability R&D must be completed. Outside the fuel development and fuel cycle demonstration elements (assumed to be under the development scope of the AFCI program), viability issues were identified during the Generation IV Technology Roadmap in safety and reactor technology.

Given that the oxide-fueled SFR was under development in Japan, the activities included here are those relevant to the metal-fueled SFR. The viability safety issues identified in the Roadmap are primarily related to the analysis and modeling of bounding accidents and include:

- long-term coolability of metal debris after a bounding accident;
- in-vessel debris retention for metal fuel; and
- experimental evidence that molten metal fuel will drain from the core to prevent recriticality.

Further, the Roadmap identified the need for availability of experimental facilities that include tests with fuel and sodium.

The schedule for the experimental program for these viability issues is very tight if the viability must be demonstrated by 2010 given that experiments can be started only in 2006 at the earliest. To meet these schedule requirements, all the detailed experimental planning would have to be done during FY2005.

Required Scope:

In interaction with the ACFI program, the preliminary fuel cycle conditions and requirements for an actinide-management SFR will be established. On the basis of these operating requirements, the remaining development needs for the SFR, with emphasis on safety-related elements, will be identified and documented.

A report with identification of remaining safety viability R&D will be prepared and will include the program plan for the investigation of bounding events.

An experimental plan will be developed to support the resolution of remaining safety-related SFR viability.

Target Scope: None.

6.2 Interaction with GIF on SFR

Required Scope: Interface with Generation IV International Forum, in particular with the GIF countries leading the SFR development effort to optimize effectiveness of R&D plan and to maintain cognizance of progress in SFR development. Interface with the ACFI Program on fuel and fuel cycle development activities for their relevance to the SFR. Interface with the crosscutting activities for relevance to SFR.

Actual Scope: Same as required scope.

Table 2 Summary of SFR Level 4 Tasks for FY 2005 ($K)

Task	Total	
	Required	Target
System Design and Evaluation	$	0
Interaction with GIF	$	$
Total	**$**	**$**

No milestones are associated with the activities at the target level in FY 2005.

7 TEN-YEAR PLAN (FY 2004 – FY 2013)

7.1 System Design and Evaluation

Required Scope:

Only the activities within the Generation IV system development are addressed in this section. Development of ceramic fuels, advanced aqueous processes, dry process systems other than pyroprocess, and large, monolithic power plant systems are under development under programs in other GIF countries and not addressed under Generation IV. Fast spectrum reactor fuel development and processing (pyroprocessing in particular) in the U.S. belongs programmatically to the ACFI Program.

The R&D objectives for the SFR under the Generation IV program are primarily related to the System Design and Safety:

- Identify plant cost reduction features, including potential development of advanced steam generator concepts, and evaluate their feasibility and potential.
- Establish the technical basis for passive safety and understanding bounding accidents.
- Coordination of activities
  - Interface with ACFI Program on fuel and fuel cycle development
  - Interface with Crosscutting activities for relevance to SFR
  - Interface with Gen IV International Forum to optimize effectiveness of R&D plan

Only the viability issues related to safety will be included here. Additional items identified during the Roadmap and pertaining to the reactor technology are:

- In-service inspection and reparability (ISI&R) technologies.
- Advanced high reliability steam generators.

The development of these technologies would likely not be completed before the technology selection and may need to be addressed during the preliminary design phase. Similarly, R&D elements intended to develop engineering solutions for lowering the capital costs of the SFR are assumed to be performed during the preliminary design phase.

The cost and schedule estimates developed during the Technology Roadmap for the safety viability issues are as follows:

- Long-term coolability of metal debris after a bounding accident: $5-10M (for both oxide and metal), medium duration (2-5 years)
- In-vessel debris retention for metal fuel: $1-2M in the medium term (2-5 years) and potential additional experiments in the medium to longer term.
- Experimental evidence that molten metal fuel will drain from the core to prevent recriticality: $3-6M plus possible additional experiments, medium duration (2-5 years).
- Availability of out-of-pile experimental facilities: $5-10M with short to medium duration (1-5 years).

The cost estimates and duration of the experimental activities were developed during the Generation IV Technology Roadmap. During FY2005, at the required level of funding, specific experimental plans would be developed with detailed schedules and cost estimates.

Beyond the technology selection, the two higher-priority reactor technology elements identified in the Roadmap:

- Development of ISI&R technologies: $20-50M with long duration (5-10 years).
- Development of advanced steam generators: $50-100M with a long to very long duration (more than 10 years).

Note that, if the SFR technology were selected in FY2010, a design activity would be started in preparation for the construction phase. This is not included in the R&D needs identified here. Furthermore, the design activity would identify additional areas of performance R&D that would be required to complete the system design.

The cost estimates for this required R&D scope between FY2005 and FY2013 is shown in Table 3.

Table 3. Cost estimate for required scope to conclude viability demonstration by 2010 and perform higher-priority R&D after technology selection ($M).

Task	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	TOTAL
System design and evaluation: experimental plan management									
Debris Coolability									
In-vessel retention									
Recriticality prevention									
Facilities									
ISI&R									
Steam Generators									
TOTAL									

Actual Scope: None expected.

7.2 Interaction with GIF on SFR

Required Scope: Interface with Generation IV International Forum, in particular with the GIF countries leading the SFR development effort to optimize effectiveness of R&D plan and to maintain cognizance of progress in SFR development. Interface with the ACFI Program on fuel and fuel cycle development activities for their relevance to the SFR. Interface with the crosscutting activities for relevance to SFR.

Actual Scope: Same as required scope.

The cost estimates for the 10-year period are shown in Table 4 at the required and target levels.

Table 4 Ten-year (FY04-FY13) budget profile for SFR Level 3 activities ($K).

Task		FY 04	FY05	FY06	FY07	FY08	FY09	FY10	FY11*	FY12*	FY13*
System Design and Safety	Required										
	Target										
Interaction with GIF	Required										
	Target										
TOTAL	**Required**										
	Target										

*Note: only higher-priority elements in the Reactor Technology R&D included here. An additional Performance R&D plan would be developed if the technology was selected in 2010.

8 PERFORMANCE MEASURES FOR FY 2005 AND FY 2006 TO FY 2013

The performance measures for the ten-year plan are as follows:

At required Funding Level

a. FY05 Performance Measure

Establish and document remaining specific safety viability R&D needs.

Develop an experimental plan to support the resolution of remaining safety-related SFR viability issues to confirm the performance of the SFR in meeting the Generation IV Technology goals on safety.

b. FY06-13 Performance Measures

Resolution of safety viability R&D issues for the metal-fueled SFR, in particular validated modeling and experimental verification of long-term debris coolability after bounding accidents, in-vessel debris retention, and recriticality prevention.

Initiation, after technology selection in FY 2010, of higher-priority reactor technology R&D programs: ISI&R and advanced steam generator development.

At target Funding Levels

a. FY05 Performance Measure

Collect information on SFR-related R&D in Generation IV International Forum countries to support the future development of the SFR R&D plan for Generation IV.

b. FY06-13 Performance Measures

Collect information on SFR-related R&D in Generation IV International Forum countries to support the future development of the SFR R&D plan for Generation IV.

The specific deliverables for the 10-year SFR plan are as follows:

FY2004

Required funding

n/a

Target funding

- Periodic reporting on GIF SFR Steering Committee activities.

FY2005

Required funding

- A report with identification of remaining safety viability R&D will be prepared and will include the program plan for the investigation of bounding events one.
- An experimental plan will be developed to support the resolution of remaining safety-related SFR viability
- Periodic reporting on GIF SFR Steering Committee activities.

Target funding

- Periodic reporting on GIF SFR Steering Committee activities.

FY2006 to FY2009

Required funding

- A progress report for each element of the experimental program to resolve safety-related viability R&D items.
- Report on status of experimental facilities to support safety-related experimental program.
- Periodic reporting on GIF SFR Steering Committee activities.

Target funding

- Periodic reporting on GIF SFR Steering Committee activities.

FY2010

Required funding

- Final report on resolution of safety viability issues for the metal-fueled SFR to support technology selection.
- Periodic reporting on GIF SFR Steering Committee activities.

Target funding

- Periodic reporting on GIF SFR Steering Committee activities.

FY2011- FY2013

Required funding and target funding: TBD